HIGH-CLASS SYSTEM FOR MAGNETOMETERS CALIBRATION AND EMC STUDY - TEST RESULTS AND DEVELOPMENT TRENDS

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Abstract.

The measurement of the Earth's magnetic field and of the other weak magnetic fields is a peculiar problem connected with extremely large range of the measured signal. It is because the level of the measured signal can be even lower than a few of picotesla at the mean Earth's field background about 50 microtesla, what gives ~140 dB of dynamic range.

This means that the instrument intended for the measurement has to cover such a wide dynamic band. For this two main problems have to be solved: as low noise as possible of the sensor and as high stability as possible of the compensation system. Both these problems were studied in Lviv Centre of Institute of Space Research (LCISR) and the obtained results allowed to create a set of high-class flux-gate LEMI type magnetometers.

The second task - high stability compensator -seems to be of more general interest for the metrology and because of this will not be considered more in this particular paper devoted to the flux-gate magnetometers (FGM) and their application. But the decreasing of the sensor magnetic noise (MN) is a very specific task and finally this parameter determines the FGM quality.

That is why a special attention was paid below to MN study, especially to the most important characteristic of MN – its spectral distribution. The physical and mathematical models which were used originally for the analysis of the MN frequency spectrum, predict its uniform shape. But experimental results, discovered apparently for the first time in [1], showed the rise of MN spectrum in the low frequency range, what was the subject of further detailed research. It was found that MN of the flux-gate sensor (FGS) dependence on frequency $b_F(f)$ may be estimated by the following semi-empirical equation:

$$b_F(f) = b_{F0} [\, 1 + (f_0/f)^{\alpha} \,], \qquad (1)$$

where b_{F0} – minimum $b_F(f)$ value at relatively high frequencies, f_0 – corner frequency.

In the expression (1) the shape of MN frequency spectrum is determined by the terms f_0 and α. By its character MN is similar to flicker noise, for which α=1 (and even more than 1) is usually taken. However our detailed research of MN frequency spectrum for different materials and designs in frequency band down to 1 mHz showed that the value of α for FGS has to be accepted in limits of 0.75...0.8. This apparently small difference gives principally other results as to the MN power calculation. Really, let us estimate the MN root-mean-square value B_{sq}:

$$B_{sq} = \{ \int_{fmin}^{fmax} b_F(f)\, df \}^{1/2} = \{ b_{F0} [\, f_{max} - f_{min} + f_0^{\alpha} (f_{max}^{\,1-\alpha} - f_{min}^{\,1-\alpha}) / (1-\alpha)] \}^{1/2}, \qquad (2)$$

where f_{max} and f_{min} are maximal and minimal values of full frequency band of FGM.

For α = 1 equation (2) is transferred to

$$B_{sq} = b_{F0} [\, f_{max} - f_{min} + f_0 \ln (f_{max}/f_{min})] , \qquad (2a)$$

what means that the more observation time increases the more noise deviations are approaching to infinity. But it is not observed in practice - even during one year of observation (what corresponds to $f_{min} \cong 3 \cdot 10^{-8}$ Hz) the zero level of FGM changes in rather narrow limits. This is because of logarithmic increasing of B_{sq} value while $b_F(f)$ is growing hyperbolically when $f_{min} \to 0$. Even the $b_F(f)$ increasing by many orders leads to only moderate growth of B_{sq}.

In order to explain this let us proceed as follows. B_{sq} value is determined on the interval from f_{min} to f_{max} . Its growth when f_{min} is decreased (or, what is the same, observation period T_{max} is increased) is convenient to estimate in relative units. In early FGM developments the corner frequency f_0 was about some hundreds Hz. Further, especially because ring-core and race-track FGS were developed, the value of f_0 in the majority of the cases was reduced up to ~1 Hz and even below. Let us take as comparison base the noise signal with constant density $b_F(f)=b_F(f_0)$=const and corresponding B_{sq} value determined as $B_{sq}(T_0)= B_{sq}(1\text{ s})$, when f_0 = 1 Hz . The $B_{sq}(T_{max}) / B_{sq}(T_{min})$ ratio is presented on Fig. 1, solid plot for α=1, dashed plot for α=0.75. For comparing at Fig. 1 is also presented relative $b_F(f)$ dependence for a=1 and a=0.75 correspondingly (upper pair).

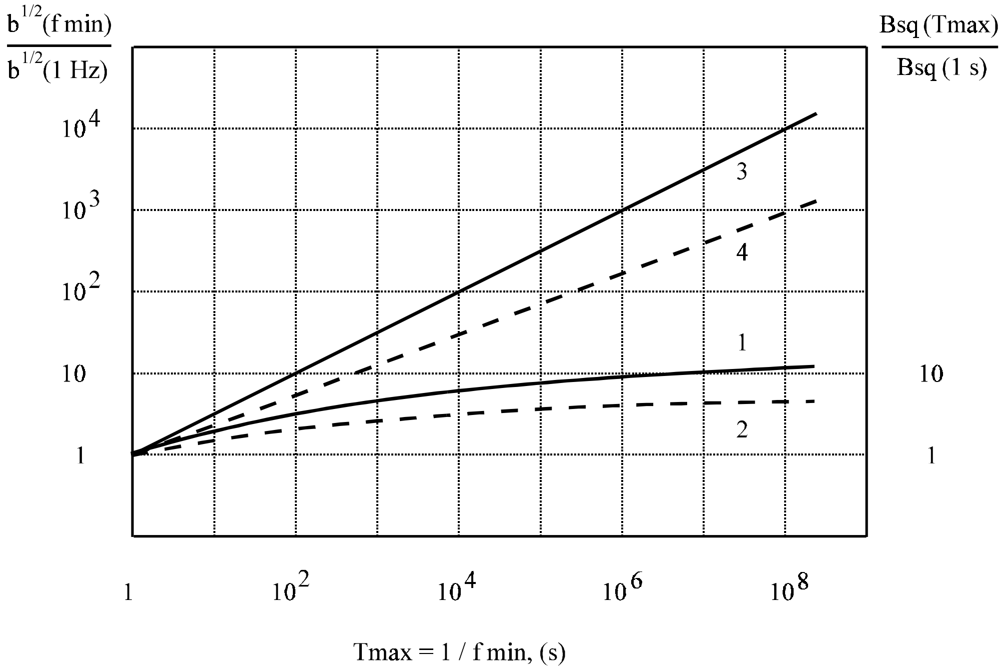

Fig. 1. Magnetic noise peak growth with $f_{min} \to 0$

It is interesting to stress that for the observation time equal to 1 year the square-root of MN density augments in ~5500 times, but B_{sq} is only 11 times higher relatively to uniformly distributed $b_F(f)=b(f_0)$ density. It is seen also that for periods from 1 day to 1 year the ratio between B_{sq} values for α=0.75 and α=1 is ~2.2...2.5, what is essential but not coincides with «infinite» growth of $b_F(f)$.

It follows also from equations (2, 2a) and Fig. 1 that even for 1 year period the calculated value of peak-to-peak MN deflection (see equation (2b) below) for typical FGM with $b_{F0} \cong 10$ pT/Hz$^{1/2}$ is in good enough agreement with experimental data obtained in practice - 1...2 nT. Thus, extremely low-frequency MN process obeys to the law as usual infra-low-frequency one and expressions (1, 2, 2a) may be used in the frequency band approaching zero too.

This high level of parameters is assured first of all by using the ferroresonance excitation mode of flux-gate sensors (FGS). Theoretic and experimental study allowed the realization of all advances of this mode, especially low power of excitation together with deep magnetization of the sensor core [2]. Other peculiarities are special design of some electronic units [3] and selection of materials for sensor construction with thermal dilatation less than 1 ppm.

A range of flux-gate magnetometers for different applications is developed at LCISR. For field use three basic models of three-component magnetometers found the most wide application: LEMI-004, LEMI-008, LEMI-009. LEMI-004 magnetometer is the simplest version with LCD display and analog output. The offset regulation is made using stepwise and smooth offset control knobs. This version is low-cost and useful for any applied research. Further improvement of this magnetometer is LEMI-008 one. Being also manually controlled, it has already both analogue and digital outputs, GPS timing of data sampling and inner memory which allows about one month of autonomous operation. One further option of this magnetometer is special anti-tilt sensor construction which makes its installation exclusively convenient and fast. The LEMI-009 version is fully automated digital magnetometer having all options of LEMI-008 magnetometer. Common features of all these versions are very low noise, high thermal and temporal stability and low power consumption. Typical figures for main parameters of these magnetometers are presented in the Table 1.

Table 1. Main parameters of LEMI-008 and LEMI-009 magnetometers

1	Full measuring range	± 100 000 nT
2	Noise in the frequency band 0.03-1 Hz, rms: ordinary version special low noise	 < 20 pT < 5 pT
3	Sensor orthogonality error	< 30 min of arc
4	Long-term drift	< 5 nT/ year
5	Thermal drift	< 0.2 nT/ °C
6	Operating temperature range	minus 10 … + 40 °C
7	Power consumption	< 2.5 W
8	Mean weight: sensor with support electronic unit	 1.7 kg 3.0 kg

The frequency band of FGM application or the period of studied signals is usually from some fractions of second up to some years. When MN is discussed, the FGM users mostly name the magnetic noise as the noise in the upper part of the frequency band, whereas MN in the lower part is called «drift». As we showed, both MN and drift are physically the same noise parameters, but in different time domains. In order to have the full impression about temporal noise dependence of the FGM following temporal band share is proposed:
0,1 s - 100 s - flicker noise (f-band);
1 m - 100 m - short-term noise (s-band);
1 h - 30 days - mean-term noise (m-band);
1 day - 365 days - long-term noise (l-band).
Such division of time bands is not arbitrary. It is connected with different possible application area of FGMs. So, f-band noise allows to estimate the FGM applicability for magnetic pulsation study. Also the methodology of noise investigations in this band differs from this in other bands. S-band noise is interesting for the application of FGM for mineral deposits prospecting. M-band is the time periods used for magnetotelluric investigations. And last but not least l-band noise is very important for observatory practice and it determines especially the necessary periodicity of absolute measurements. In all these bands the FGM noise was tested.

The special laboratory equipment developed and installed in LCISR allows to make detailed noise power tests in f-band. The typical time dependence for LEMI-004 FGM noise power spectrum is shown on Fig. 2.

Very low value of corner frequency f_c and good noise uniformity at higher frequencies are clearly seen. These tests particularly prove that this magnetometer excellently suits for magnetic pulsation study, the frequencies of which are within f-band.

For the tests in other bands a two-poles low-pass filter was installed at FGM outputs. Both the s-band and m-band noises were tested at Belsk Observatory (Poland), the basic magnetometer of which is of torsion type (PSM). This type magnetometers are especially good in mentioned temporal bands because of inherently low level of suspended magnet own oscillations if the temperature of the environment is strictly stabilized. In Belsk Observatory the temperature in reference magnetometer hut is maintained in the limits within ±0,1 centigrade.

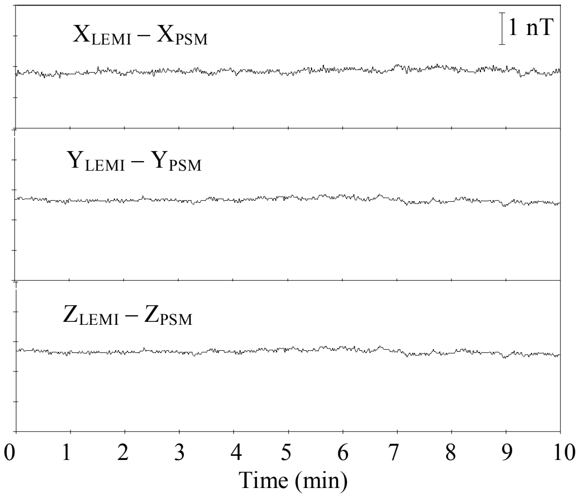

Fig. 3. FGM s-band noise

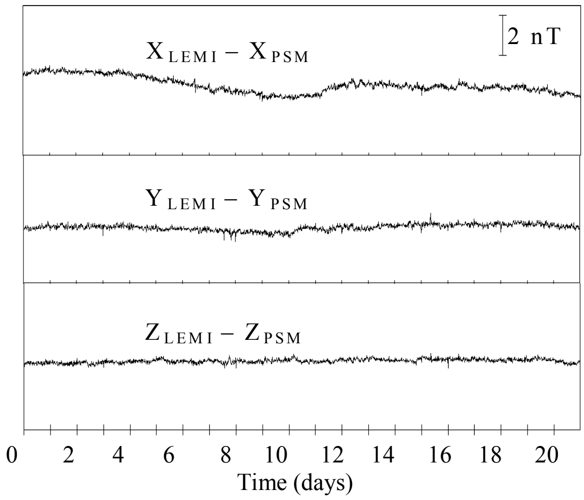

Fig. 4. FGM m-band noise

Fig. 3 illustrates the results of s-band tests. The resolution of registration unit was 30 pT/bit only and sampling was made once per second without averaging. Then the LEMI-004 s-band noise was estimated as the difference between output signals of X, Y, Z channels of LEMI and PSM. Special measures were taken in order to eliminate the time shift influence between the samplings of reference and tested magnetometers channels. The 10-minutes intervals were randomly chosen for tests in the day time when the activity of Earth's magnetic field was relatively low. It is well seen that the s-band noise is mainly within ±1 digit or about 50 pT.

The same methodology was used for m-band noise estimation. First the 30-seconds averaging of 1-second samples for each channel was made in the registration unit and then 2-minutes mean was constructed as one point at Fig. 4. The m-band noise for Z-component can be estimated as very good - about 0,3 nT/month. For X and Y components these numbers are about 1.2 nT/month and 0.5 nT/month respectively. But to this it is necessary to make following objections.

First, the tested LEMI-004 was placed outside of reference hut and no special pier and thermal stabilization was used.

Second, for the applied methodology of noise investigation very important is to have as good as possible alignment of sensor components of both reference and tested magnetometers. For Z-component it is possible to have always good alignment, but for X and Y axes to get the alignment error less than 30' is very difficult. As a result, in the plot for X-components difference we have a trend correlated with Y-component of magnetic field variations and in the plot for Y-components difference - correlated with X-component of the field.

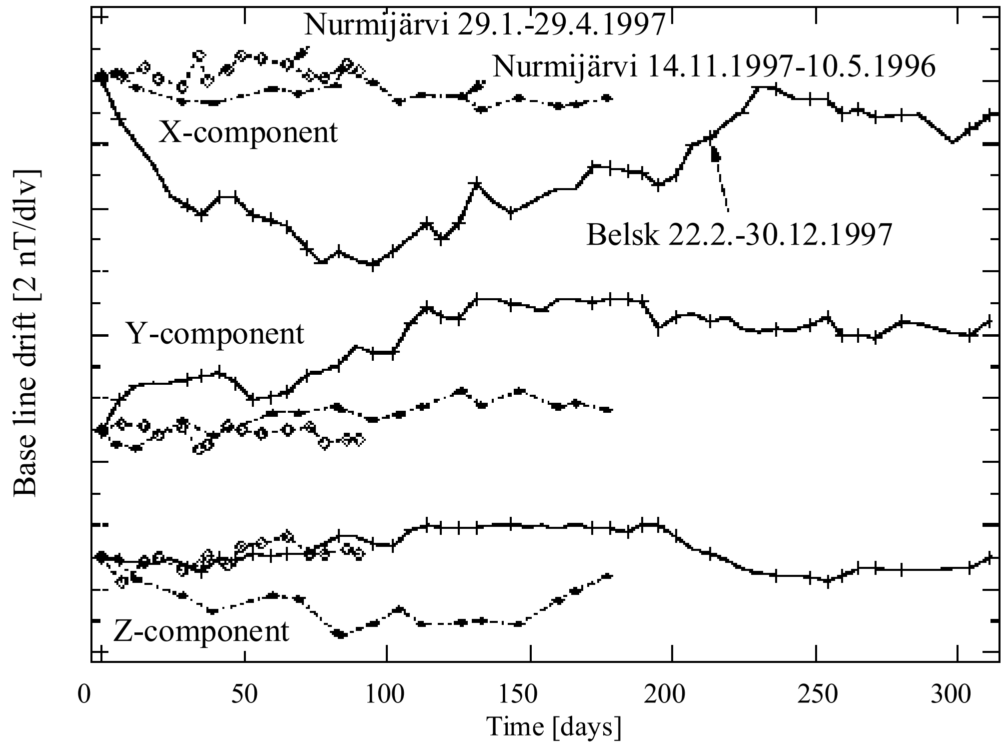

Fig.5. FGM l-band noise

The most complicated is the l-band noise investigation and not only because it needs very long time. In this time domain absolute measurements only can be the reference for noise calculation. In order to be as much sure in the obtained data as possible these tests were made with different specimens of LEMI-004 magnetometers in Belsk and Nurmijarvi (Finland) Observatories. The results are presented on figure 5 and the marks on the plots correspond to the times of absolute measurements made by Observatory staffs.

Analyzing the results of l-band tests the objections to the precedent results also have to be taken into account. Even without them it is possible to conclude that for all 3 randomly chosen tested magnetometers the l-band noise was within INTERMAGNET standard requirements, i.e., no more than ± 5 nT/year. For the best of them this value was 2-3 times less.

Certainly, such high level of parameters has to be confirmed by corresponding metrological certification. To create the installation able to calibrate the FGM with necessary precision is an extremely difficult problem. Moreover, there is no reference measure of weak magnetic field, what additionally complicates the situation. One of the first attempts to design the high class calibration system was made in Finland.

A three axes coil system following the design by Alldred and Scollar [2] was built at the Nurmijarvi Geophysical Observatory in 1986 and was installed in a calibration room to its present site in 1990 [3]. The system consists of three sets of four square coils with diameter from 1.6 to 2.1 m. It can produce a uniform field with the error less than 10^{-5} in a volume of diameter of about 30 cm at the center of the system and a non-uniformity less than 10^{-4} should be reached in diameter of 40 cm. The aluminum frames of the coils are sitting on a 70 x 70 cm^2 top of a concrete pillars. There is a pillar made of glass bricks and a marble plate on the concrete basement which serve as a non-magnetic stable base for the tested instruments. The room is temperature stabilized and made of non-magnetic materials.

The orientation of the coils was of the first measured using the sun as a direction reference. With the help of a theodolite the X-axis was directed to the geographic North and the Y-axis to the East. The vertical Z-axis is positive down as the Earth's magnetic field is in the northern hemisphere. A final orientation was done by measuring the direction of the magnetic fields generated by the coils. This was done with the non-magnetic theodolite having a magnetic sensor connected to its telescope. With this method the non-orthogonality of the magnetic axes of all the coil couples was found to be less than 0.5 arc minutes.

The coil constants were measured by using a proton precession magnetometer in the center of the coils. The Earth's field of two of the three components were first compensated to a value close to zero. Then large positive and negative fields were generated in the third component and the field in the center of the coils was measured by using the proton magnetometer. By this method the coil constants can be measured with an accuracy of 0.005 %.

A reference magnetometer, which is in the variation room about 100 meters apart, is connected to the system through a local area network, and is used to record the natural field variations during the calibration.

The current control is organized by three channel 18 bit digital to analog conversion of the desired current values to control the voltages on the inputs of the three current sources. An analog memory is used to maintain the input voltage between the control sequences. The currents are regulated until they meet their nominal values with deviation less than 0.03 mA what corresponds to 1 nT magnetic field in the centre of the coils.

The current is measured using three one-ohm precise resistors. Their temperature dependences between 20 and 30 deg. C were measured and the effect corrected. A fourth current measuring unit was installed in the system also. It is based on extremely precise current comparator and now it allows to measure the currents up to ± 3 A with accuracy better than 0.002%. This new current meter is used to calibrate three other meters. The voltage over the resistors as well as the voltage from the output of the tested magnetometer is measured by a 24 bit analog to digital converter.

The software for the calibration system uses the C language in LINUX environment. During the operation the computer display shows the desired currents, the measured currents, voltage output of the tested magnetometer and the Earth's magnetic field as measured by the reference magnetometer. The usual time step between current regulations is 10 seconds, but can be also changed as desired.

The software has three main operation modes. In the manual mode the operator writes the current values one by one using the keyboard. This is mostly used for testing and calibrating the system itself. In the second mode an input file with current values is written in advance and the software runs this file. This allows to design special magnetic field configurations like a rotating field. With the third mode an automatic calibration can be done. The software asks for certain parameters like the maximum current or field and the number of measurements, and then it starts running the calibration. After execution all the measurements it calculates the results. This cycle can be repeated so that a file with measured data of arbitrary length is collected. Thereafter, the output file can be analyzed to get statistically reliable results and also to study possible temporal drifts in the data sets.

As an example the results of a calibration that was done for one Ukrainian flux-gate magnetometer of LEMI—004 model are given. The magnetometer has measuring range ± 5000 nT (with initial magnetic field compensation possibility in the limits of ± 120000 nT) and its noise level is less than 10 pT r.m.s. in frequency band from 0.01 to 1 Hz.

The automatic mode of calibration was used. The field values generated by the system were random between chosen limits. One calibration cycle consisted of 30 random field values generated every 10 second and the calibration result was calculated after every cycle. The calibration was running until about 10 cycles were measured. All the data were collected in a file and by using other program were analyzed to get the final results. During this test the whole calibration procedure was done three times by using different maximum field limits: ± 1000 nT, ± 2000 nT and ± 4000 nT.

Table 1. Results of three calibrations of the LEMI-004 magnetometer

Field limits (nT)	± 1000	±2000	±4000
Number of recordings	436	465	490
X transformation factor (nT/mV)	0.4928	0.4928	0.4928
Y transformation factor (nT/mV)	0.4949	0.4948	0.4949
Z transformation factor (nT/mV)	0.4971	0.4971	0.4971
Angle between X and Y (deg)	90.150	90.150	90.149
Angle between Y and Z (deg)	89.836	89.836	89.840
Angle between X and Z (deg)	89.899	89.898	89.896

The results show (Table 1) that the transformation factors of the magnetometer remain stable to the fourth digit and can be measured with about 0.02% accuracy. Orthogonality of sensors is seen from the angles between the sensors as they differ from 90 degrees. The fourth digit is stable again and therefore the error of the angle measurements is less than ± 0.5 arc minutes. The program gives also the orientation of the magnetometer sensors with respect to the coil axes. This allows calculation of an angle correction matrix which reduces data recorded by the magnetometer to the orthogonal co-ordinate system defined by the coil axis. If the magnetometer will be installed in a satellite or any other platform with known coordinates, this information can be utilized.

For this tested magnetometer the matrix is:

$$\begin{bmatrix} \mathrm{Cxx} & \mathrm{Cxy} & \mathrm{Cxz} \\ \mathrm{Cyx} & \mathrm{Cyy} & \mathrm{Cyz} \\ \mathrm{Czx} & \mathrm{Czy} & \mathrm{Czz} \end{bmatrix} = \begin{bmatrix} 0.998 & 0.066 & 0.001 \\ -0.069 & 0.998 & 0.02 \\ -0.002 & 0.001 & 1.000 \end{bmatrix}$$

Offsets of the magnetometer's components are important parameters as well. They can be measured inside a good magnetic screen if the sensors are small enough comparably to the volume of the screen. However, the coil system can be used to measure the offsets of all size of magnetometers. First, a zero field is generated and the magnetometer sensor is installed in the centre of the coils. Then the output of the magnetometer is read at first in this initial position and then after rotating all the sensors by 180 degrees. It was shown experimentally that when the Earth's magnetic field is not disturbed the accuracy of the method is about ± 1 nT.

The next important feature of the magnetometer is the drift of the readings with respect to temperature. The calibration room has a special wooden chamber standing on a pillar, which can be heated without heating the pillar. The tested sensor can be installed inside the chamber and the temperature can be increased and decreased in a controlled manner. The recording is compared with that of the observatory magnetometer, which is recorded in the special variation room with stabilized temperature. The test can be done separately also for the electronics unit of the magnetometer. By this method the temperature drift of the sensors of the LEMI-004 magnetometer was measured to be less than 0.2 nT/deg. C.

It is seen from the given example that in spite of that the reference field inhomogeneity can be made lower than 10 ppm in enough big volume and current amplitude measurements can be made better than 0.001% and the reference magnetometer of the system can provide measurements with accuracy ±1 nT or about 0.001% of the whole field value, the calibration accuracy does not allow to get error less than 0.02%. The analysis of error sources shows that one of possible cause may be the unknown residual angle between the axes of reference and calibrated magnetometers, which should be collinear. Let us analyze possible influence of this error source.

Let two magnetometers - reference and calibrated ones - have axes X_i, X_i' (i = 1,2,3) (Fig. 1). The angles α_i determine mutual orientation (collinearity) errors of both magnetometer axes.

$$\left.\begin{aligned}
&\sin\Theta(t)\cos\varphi(t)\,0.5\alpha_1^2 << \Delta H_{n,1}\left|\vec{H}_T\right|^{-1},\\
&\sin\Theta(t)\sin\varphi(t)0.5\alpha_2^2 << \Delta H_{n,2}\left|\vec{H}_T\right|^{-1},\\
&\cos\Theta(t)\,0.5\alpha_3^2 << \Delta H_{n,3}\left|\vec{H}_T\right|^{-1},
\end{aligned}\right\} \tag{1}$$

where Θ, φ are angles between Earth's magnetic field vector and reference magnetometer axes, $\Delta\vec{H}_T$ - maximum Earth's magnetic field vector beviation, $\Delta H_{n,i}$ - admissible deviation between *i*-component readings of reference and calibrated magnetometers.

The upper numeric estimation of the error introduced by non-collinearity of axes of both magnetometers in the case of random orientation of these axes relatively to $\vec{H}_T$ vector gives the following value. Let us take for estimation $\Theta = \varphi = 45°$(in this case cos Θ (or φ) = sin Θ (or φ) ≈ 1). Then

$$\left.\begin{aligned}
&\alpha_1 << 2(\Delta H_{n,1}\left|\vec{H}_T\right|^{-1})^{0.5},\\
&\alpha_2 << 2(\Delta H_{n,2}\left|\vec{H}_T\right|^{-1})^{0.5},\\
&\alpha_3 << (2^{1.5}\Delta H_{n,3}\left|\vec{H}_T\right|^{-1})^{0.5},
\end{aligned}\right\} \tag{2}$$

and substituting ΔH_T=2·10^3 nT and ΔH≈(0.1-1) nT we get from (2) $\alpha_i \approx (5\text{-}15)'$.

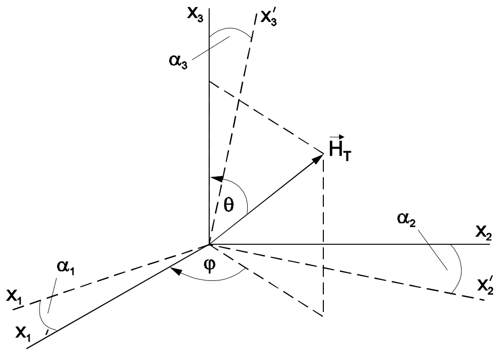

Fig. 1. Mutual orientation of reference and calibrated magnetometers axes

It is certain that such collinearity error can not be achieved, what requires further problem study in order to compensate the error introduced in calibration data.

Last year taking into account very favourable surroundings it was completed by a new magnetic cleanliness measuring system which was built in order to solve very important tasks: cleanliness study and discovered magnetic moments compensation. One of the first system applications is to serve to European and especially local satellite instruments manufacturers.

An existing reference coil system and electronics for magnetometer calibrations were utilised as basic components for the new equipment. A non-magnetic rotating table and a sensing three-component flux-gate magnetometer were installed additionally in the coil system center and corresponding interactive software was written for fast and accurate measurements. After the thoroughful research it appeared that this very important at present problem is not solved with necessary precision till now neither theoretically nor practically.

That is why in order to put the system into operation rather complicated theoretical study has to be done. The obtained equations are too cumbersome to present them here. The interrelations between the parameters of the unknown magnetic moment inside the tested body - components of the magnetic moment M (M_r, M_t, M_z) and the co-ordinates of the origin R, h, φ from one side and the components of the magnetic field H_x, H_y, H_z measured by the magnetometer placed close to the tested body from the other side were obtained. If some of the M parameters are known (e. g., position of the origin or direction) the calculation problem is rather simple and the estimated error of M modulus δ M and its direction $\delta\lambda$ determination in dependence on signal to noise ratio (*S/N*) is given in the Table.

S/N	3	5	10	20	100	∞
δ (%)	8.8	5.4	1.5	0.24	0.17	0
$\delta\alpha$(°)	20	10	5.4	2.5	0.6	$3.3 \cdot 10^{-6}$

If any M parameter is known, the calculation problem is very complicated and corresponding 6 equations consist on about 100 terms each. The corresponding error estimation is given in Table... for $M_r = M_t = M_z = 1$ A·m^2 and R = 0.1 m, h_0 = 0.3 m, $\varphi = 0$.

S/N	3	5	10	20	50	100	∞
M_r (A·m^2)	0.988	0.798	0.634	0.975	0.813	0.997	1
M_t (A·m^2)	0.899	0.663	0.606	0.963	0.791	0.996	1
M_z (A·m^2)	0.849	0.369	0.319	0.935	0.687	0.997	1
R (m)	0.0924	0.0847	0.0947	0.0956	0.0853	0.0994	0.1
h_0 (m)	0.176	0.104	0.0763	0.192	0.251	0.2	0.2
φ(°)	10.2	12.9	-25.9	-55.4	-6.36	-1.76	0

It appears that this problem can be solved with low error only for high *S/N*. To attain the stability of the method against low *S/N* further study is necessary.

References

1. R. Ja. Berkman. Fluxgate magnetometers noise and methodology of their study. Geophyziheskoje priborostrojenije, v.10, Leningrad, 1960, pp.25-43 (in Russian).
2. I. C. Williams, S. W. Noble. The fundamental limitations of the second-harmonic type of magnetic modulator as applied to the amplification of small DC signals. Proc. IEEE, 1950.
3. V. Korepanov, R. Berkman, B. Bondaruk, Advanced flux-gate magnetometers with low drift, In: *XIV IMECO World Congress. New measurements - challenges and visions (Tampere, Finland),* Topic 4, IVA, 1997, pp. 121-126.